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Derelict Fishing Gear in the Northwestern Hawaiian Islands: Diving Surveys and Debris Removal in 1999 Confirm Threat to Coral Reef Ecosystems

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Marine debris threatens Northwestern Hawaiian Islands' (NWHI) coral reef ecosystems. Debris, a contaminant, entangles and kills endangered Hawaiian monk seals (*Monachus schauinslandi*), coral, and other wildlife. We describe a novel multi-agency effort using divers to systematically survey and remove derelict fishing gear from two NWHI in 1999. 14 t of derelict fishing gear were removed and debris distribution, density, type and fouling level documented at Lisianski Island and Pearl and Hermes Atoll. Reef debris density ranged from 3.4 to 62.2 items/km^2. Trawl netting was the most frequent debris type encountered (88%) and represented the greatest debris component recovered by weight (35%), followed by monofilament gillnet (34%), and maritime line (23%). Most debris recovered, 72%, had light or no fouling, suggesting debris may have short oceanic circulation histories. Our study demonstrates that derelict fishing gear poses a persistent threat to the coral reef ecosystems of the Hawaiian Archipelago. Published by Elsevier Science Ltd.

Keywords: Marine debris; contaminants; Hawaiian monk seal; coral reef; fishing; Northwestern Hawaiian Islands.

Introduction

While land-based sources may be responsible for most marine debris in the world's oceans (Coe and Rogers, 1997), in some geographic areas, characterized by distinct bathymetry, relative geography, and critical habitat for endangered species, debris having maritime origins may pose the greatest threat to ecosystem health. One such area is the Northwestern Hawaiian Islands (NWHI), comprising 69% of the United States' (US) coral reefs by area (Miller and Crosby, 1998). On the basis of opportunistic surveys of these islands in 1996 and 1997, scientists reported the reefs were suffering from substantial anthropogenic damage, primarily from contaminants consisting of derelict fishing gear (Boland, unpub. data).

NWHI bathymetry and relative geography subjects the islands to marine debris from fisheries throughout the Pacific Rim (Kubota, 1994; Brainard *et al*., 2000a; Ingraham and Ebbesmeyer, in press). Gear intentionally discarded, or unintentionally lost in storms or active fishing operations, may circulate for years in ocean gyres and currents (Ingraham and Ebbesmeyer, in press), until eventually encountering a shoal on which it snags. Shallow NWHI reefs, extending some 1200 miles, function in this manner. Once derelict fishing gear are caught on NWHI coral reefs, it begins a cycle of destructive activity. Derelict fishing gear damages coral substrate comprising the reef structure; some derelict nets recovered had 20% of their weight attributable to broken coral fragments (Boland, unpub. data). Presumably, after derelict fishing gear snags on reefs, wave action acting on the debris breaks coral heads on which the debris is held, freeing the debris to subsequently snag and damage additional corals.

Movement of derelict fishing gear across shallow reefs destroys benthic reef flora and fauna and entangles macrofauna, including threatened and endangered species. All marine turtle species occurring in Hawaiian waters, including endangered hawksbill (*Eretmochelys*

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imbricata), olive ridley (*Lepidochelys olivacea*) and leatherback (*Dermochelys coriacea*) sea turtles, as well as threatened green sea turtles (*Chelonia mydas*) have documented entanglement records (Balazs, 1978, 1980, 1985; Henderson, 1984). Most of these accounts document turtles that died due to entanglement or would have died without human intervention. Derelict fishing gear entanglement is a known cause of mortality to critically endangered Hawaiian monk seals (*Monachus schauinslandi*). All main Hawaiian monk seal breeding subpopulations are within the NWHI, and suffer one of the highest entanglement rates of any seal or sea lion reported to date. From 1982 to 1998, annual Hawaiian monk seal population entanglement rates were 0.18–0.85% as compared to 0.15–0.71% during 1967–1992 for juvenile male northern fur seals (*Callorhinus ursinus*), a species for which entanglement has been proposed to explain decreasing population trends (Henderson, 1990, 2001; Fowler *et al.*, 1993). In 1999, 25 Hawaiian monk seals were entangled, the greatest yearly number since records have been kept, representing approximately 1.7% of the total population. Published entanglement rates represent a conservative estimate of animals lost to derelict fishing gear, as documented entanglements are almost exclusively generated from animals able to swim ashore or washed ashore dead. Reliable estimates of animals entangled and dying at sea are not available. In addition to marine mammals and turtles, seabirds, fish, and crustaceans are at risk from derelict fishing gear entanglement (Harrison, 1983; Breen, 1990).

Our study is part of a multi-agency effort to address the problem of derelict fishing gear in the NWHI, and the first to use divers to systematically survey and remove marine debris. Our objectives are to: (1) remove submerged and beached derelict fishing gear from the NWHI, (2) estimate density and describe distribution of derelict fishing gear in representative NWHI, and (3) characterize recovered debris by type, function, and organic fouling.

Methods

Our methodology evolved from NWHI marine debris efforts conducted from 1996 to 1998 to mitigate Hawaiian monk seal entanglement (Boland, unpublished data). Previous work at French Frigate Shoals and Pearl and Hermes Atoll (PHA) surveyed approximately 4 km^2 of coral reef habitat to depths of 10 m and recovered 11 868 kg of derelict fishing gear (Boland, unpub. data). Using results from Boland, we formulated a practical debris survey and removal plan which included: (1) identification of High Entanglement Risk Zones (HERZ) for Hawaiian monk seals, (2) survey methodology appropriate for variable atoll physiographic features, and (3) debris removal methodology.

High entanglement risk zones

Two NWHI sites with high rates of Hawaiian monk seal entanglement and marine debris were selected as study sites: Lisianski Island (LIS) and PHA (Henderson, 1984, 2001; Boland, unpub. data; Fig. 1). Coral reef areas with expected high debris densities used by Hawaiian monk seals as nursery grounds were defined as HERZ (Westlake and Gilmartin, 1990; Boland, unpub. data). HERZ were characterized by extensive barrier or patch reefs that, while affording monk seal pups protection from shark predation (Westlake and Gilmartin, 1990), provided a shoal on which debris accumulated (Boland, unpub. data). As northeastern winds prevail in this region, debris accumulation would be expected on northeastern facing shores. The HERZ were located inside the

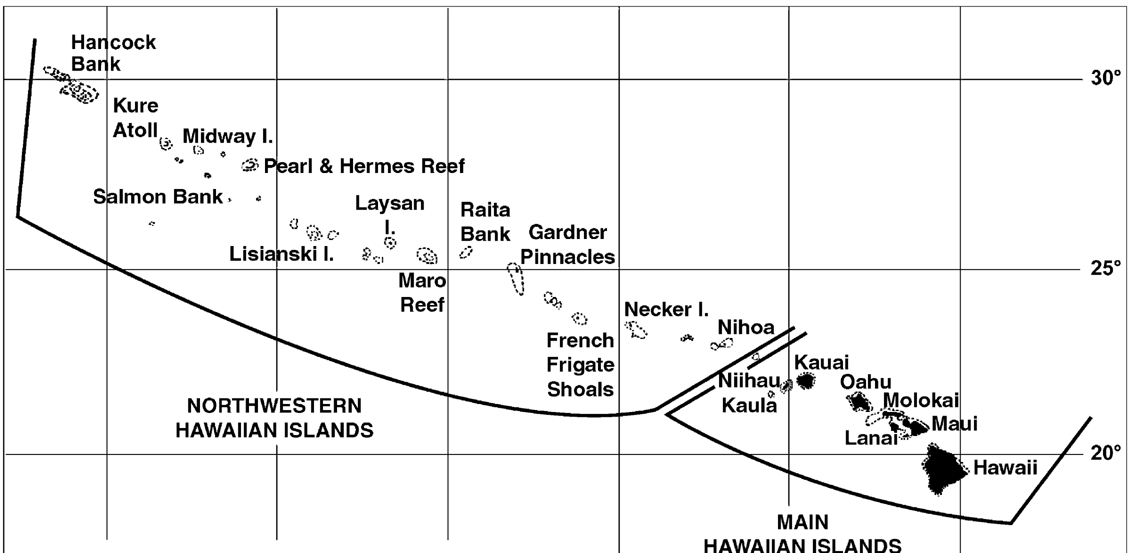

Fig. 1 Hawaiian Island Archipelago.

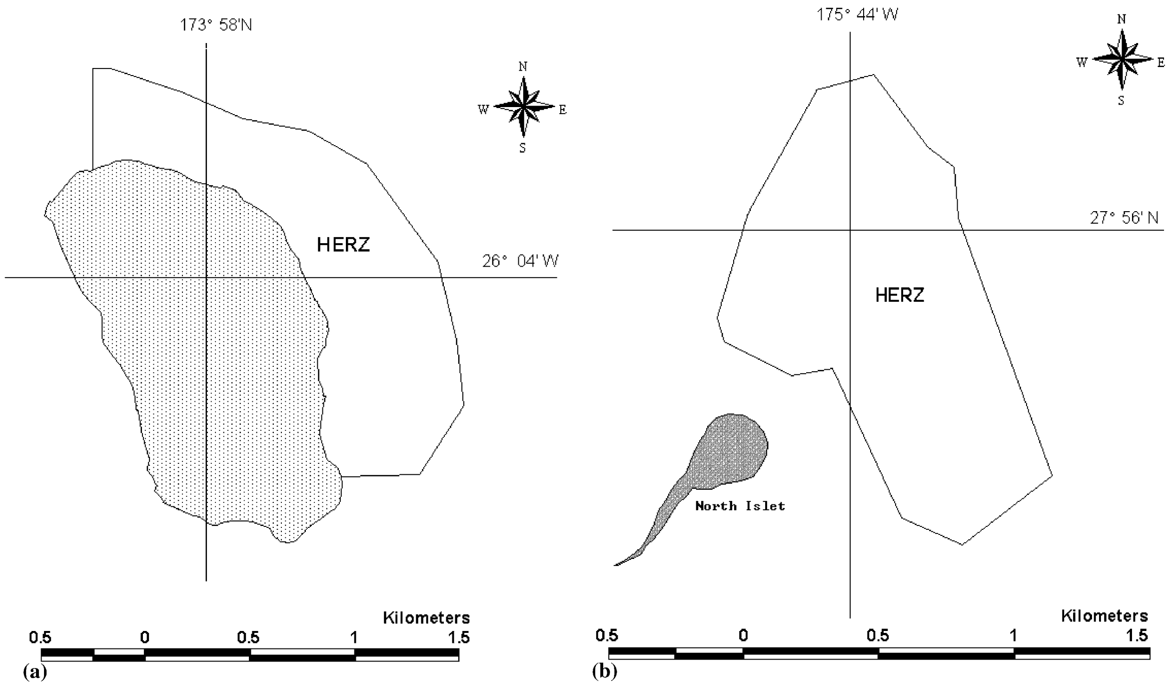

Fig. 2 HERZ associated with: (a) Lisianski Island and (b) Pearl and Hermes Atoll, North Islet.

barrier reefs at the sites' northeasterly ends; associated with LIS proper and North Islet at PHA (Fig. 2).

In-water survey methods

The US National Oceanic and Atmospheric Administration (NOAA) 164-foot ship *Townsend Cromwell* and the 225-foot US Coast Guard (USCG) Cutter *Walnut* were dedicated support platforms during the study, 6 October–4 November 1999. Smaller craft were dispatched from support vessels to conduct surveys for submerged derelict fishing gear. Previous NWHI studies suggested most reef-hung derelict fishing gear was located in waters of less than 10 m (Boland, unpublished data). To maximize debris removed, and facilitate comparison to previous work, submerged derelict fishing gear surveys were completed within the 10 m isobath around LIS up to 0.5 nmi offshore, and in areas of 10 m or less at PHA. HERZ surveys were completed first, followed by those in additional areas of less than 10 m depth. All surveys were conducted using a small boat, coxswain, and snorkel divers.

Debris surveys were conducted by two snorkel divers towed approximately 10 m behind a small boat at 1–2 km, visually inspecting the water column using strip transects approximating a parallel track search pattern (Ribic *et al.*, 1992). During surveys divers held plywood boards (90 cm × 30 cm × 2 cm) to steer themselves in an oscillating pattern from the surface to depth while serpentining laterally. Surveys were conducted only when divers could observe the sea floor easily from the water surface, and thus we assumed a uniform vertical detection probability. The effective transect swath width was determined by water clarity. Water visibility was estimated by divers at the onset and conclusion of each transect by recording the maximum distance a small green trawl net fragment (<5 m^2) suspended 1 m below the sea surface was visible. For each transect, the potential visible swath width was estimated at two times the mean of the initial and final water visibility estimates. The effective swath width was the lesser of the potential visible swath, or 15 m, the maximum width we expected divers to be able to uniformly detect debris present. Therefore, we assumed a uniform detection probability within the effective sampling swath. Transects were documented using handheld Global Positioning Systems (GPS; Precision Lightweight GPS Receiver (PLGR), Rockwell International), downloaded to a personal computer daily. GPS data were analysed with Geographic Information Systems software. The area surveyed was estimated as the product of the transect length and effective swath width. Debris density was estimated by dividing the total number of debris items found by the area surveyed.

Debris found was marked with a floating buoy and location documented by GPS. Debris size was visually estimated in situ:

Class 1: fragments of net or line; less than 5 m^2.
Class 2: small amount of net or line; approximately 5–10 m^2.
Class 3: moderate amount of net or line; approximately 11–25 m^2.
Class 4: large amount of net or line; greater than 25 m^2.

On-land debris collection

All derelict fishing gear on land were removed from the two study sites. Most derelict fishing gear washing ashore at these sites is removed from beaches and deposited in inland heaps by US National Marine Fisheries Service personnel to reduce Hawaiian monk seal entanglements. Therefore, size classifications and location of on-land debris are not reported. Debris type and weight are recorded for beached debris and incorporated in results below.

Removal and processing methods

Divers removed class 1 debris from HERZ during initial surveys. Debris removal outside HERZ, and for class 2 and larger debris within HERZ, was completed after initial surveys with dedicated small craft. For some debris recovery, divers used self-contained underwater breathing apparatus (SCUBA). Divers cut debris free from the substrate, using care to avoid additional coral damage. Derelict nets fully incorporated into the reef structure, and no longer an entanglement hazard, were left in place to preserve associated coral growth. These nets were not included in debris density calculations. Removed debris was transported by small craft to support vessels. Total debris weight of each boatload was determined during transfer from small craft to support vessels by scales integrated in the ships' cranes. Once onboard support vessels, debris was sorted by net type and miscellaneous lines and these component weights recorded.

Net samples from each unique debris type were evaluated by mesh size, twine diameter, strand number, twist or braid composition and direction, and knotted or knotless construction, after which samples were archived for future reference. For debris conglomerates, this information was collected for all net types present.

Organisms entangled in, attached to, or within bundles of recovered debris were opportunistically identified at least to genera. All coral fragments recovered were returned to the sea. Also noted was degree of debris epibiont encrustation (fouling) according to the following criteria:

None: 0% of debris surface area covered by fouling organisms
Light: 1–40% of debris surface area covered by fouling organisms
Moderate: 41–75% of debris surface area covered by fouling organisms
Heavy: >75% of debris surface area covered by fouling organisms

Fouling level was not determined for debris recovered on land.

Results

A total of 14.1 t of derelict fishing gear were removed from the two sites. At LIS, 911 kg of derelict fishing gear were recovered from coral reef habitat and an additional 4533 kg from beaches. At PHA, 7536 and 1140 kg of derelict fishing gear were recovered from coral reefs and beaches, respectively.

Area surveyed, debris density and distribution

Coral reef habitat surveyed, derelict fishing gear items found, and debris densities are presented in Table 1. LIS HERZ survey transects and debris distribution are shown in Fig. 3. Coral reef habitat surveyed outside the LIS HERZ included bathymetric features poorly represented in the HERZ, such as sand flats and isolated patch reefs (Fig. 4).

PHA debris distribution is presented in Fig. 5. Opportunistic debris removal at PHA outside the HERZ was conducted in an area where shallow labyrinths of coral heads and meandering barrier reefs precluded towing divers from small boats. PHA HERZ survey transects and debris distribution are presented in Fig. 6.

Debris size

Although derelict fishing gear of all size classes were present at both study sites, reef debris size trends varied by site (Table 2). Debris size was nonuniformly distributed at LIS, with significantly more class 1 items than other sizes ($\chi^2 = 45.47$, $df = 3$, $p < 0.001$). The 28 derelict fishing gear items encountered in the LIS HERZ consisted of 22 class 1, five class 2, zero class 3, and one class 4 sized items. At LIS outside the HERZ, debris encountered consisted of one class 1 and one class 2 net. Thus, 79% of LIS debris items found were less than 5 m^2.

Debris size class frequencies did not differ significantly from a uniform distribution at PHA ($\chi^2 = 3.96$; $df = 3$, $p = 0.26$). Of the 16 PHA HERZ derelict fishing gear items were two class 1, three class 2, three class 3, and three class 4 items. Five PHA HERZ derelict fishing gear items were not sized in situ. At PHA outside the HERZ, derelict fishing gear consisted of nine class 1, three class 2, one class 3, and three class 4 items. Two PHA derelict fishing gear items outside the HERZ were not sized in situ.

TABLE 1

Area surveyed, debris numbers, and debris densities for areas at LIS and PHA in 1999, including HERZ.

	Total area surveyed (km^2)	Total # debris items	HERZ area (km^2)	HERZ area surveyed (km^2)	HERZ # debris items	HERZ debris density (items/km^2)	Area surveyed outside HERZ (km^2)	Outside HERZ # debris items	Outside HERZ debris density (items/km^2)
LIS	1.02	30	1.17	0.45	28	62.2	0.58	2	3.4
PHA	*	34	1.00	0.66	18	27.3	*	16	*

*Complex bathymetry at PHA prevented estimation of total area surveyed, and area surveyed and debris density outside of the HERZ.

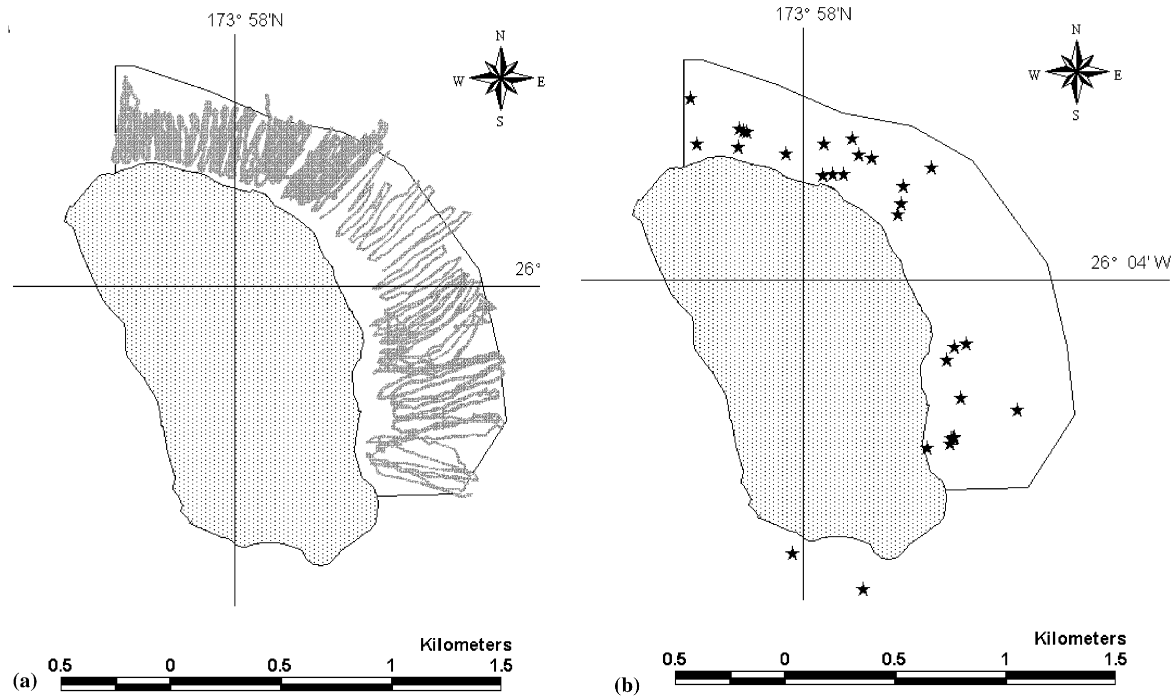

Fig. 3 Lisianski Island and associated HERZ with: (a) derelict fishing gear survey transects completed by snorkel divers indicated by the shaded lines within the HERZ and (b) location of debris items encountered noted by stars.

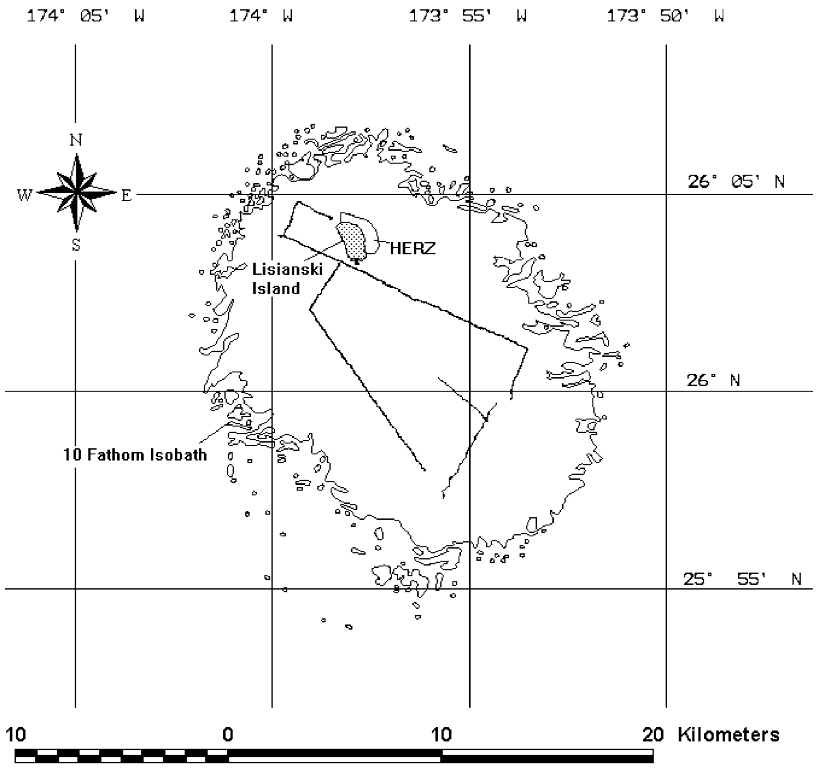

Fig. 4 Derelict fishing gear survey transects completed outside the HERZ at Lisianski Island indicated by lines. Ten fathom isobaths indicated as meandering solid line.

Debris type

Debris net types were nonuniformly represented, with significantly more trawl items at both study sites and for both sites combined (χ^2, $df = 4$, $P < 0.001$ for all; Fig. 7). Trawl netting accounted for 91% and 86% of derelict net fragments at LIS and PHA, respectively. The

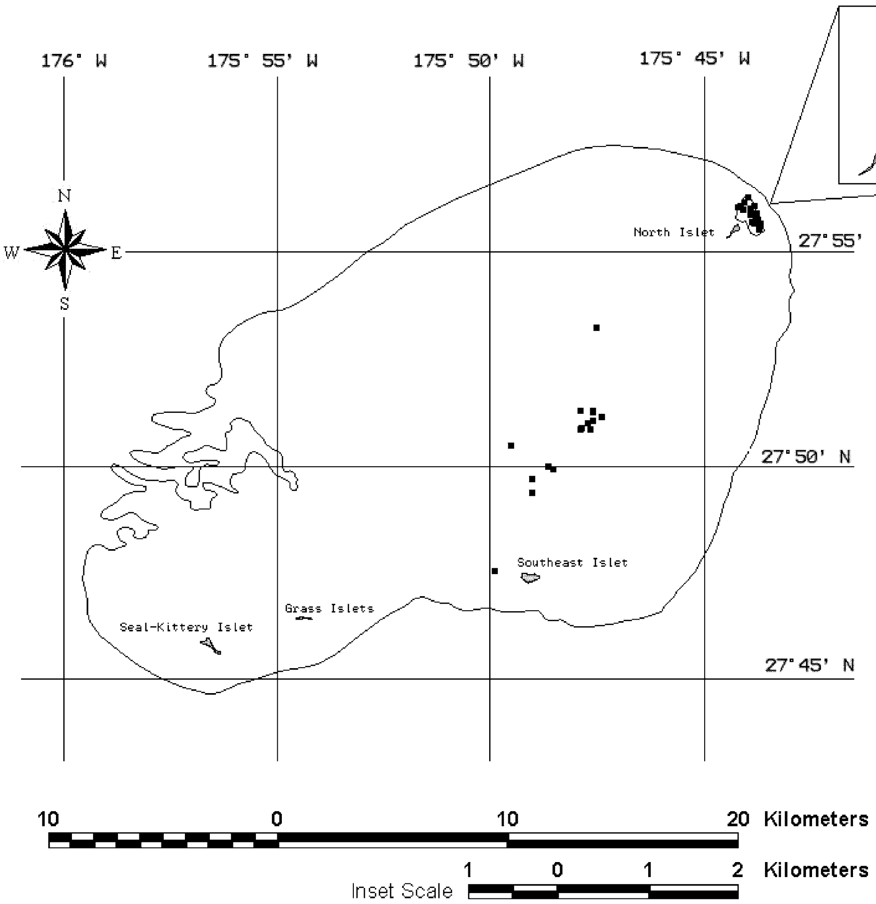

Fig. 5 Location of reef-hung derelict fishing gear at Pearl and Hermes Reef. Debris items indicated by squares. Solid line represents 10 fathom isobath around atoll. Inset of North Islet and associated HERZ.

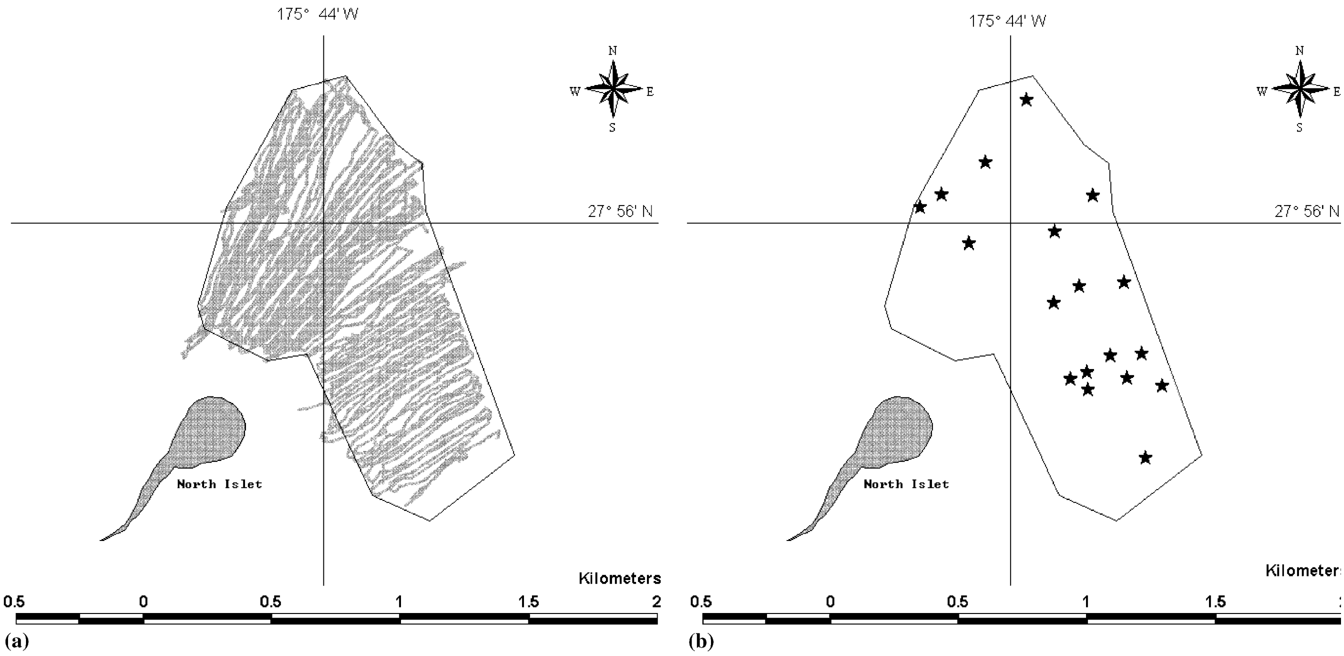

Fig. 6 HERZ at North Islet, Pearl and Hermes Atoll with: (a) marine debris survey transects completed by snorkel divers indicated by the shaded lines and (b) location of debris items encountered noted by stars.

TABLE 2

Size of debris encountered on the reefs of Lisianski Island and Pearl and Hermes Atoll, Northwestern Hawaiian Islands[a].

Debris class size	Lisianski Island	Pearl and Hermes Atoll
1	23*	11
2	6	6
3	0	4
4	1	6
Unknown	0	7

[a] Class $1 < 5$ m^2, class $2 = 5$–10 m^2, class $3 = 10$–25 m^2, and class $4 > 25$ m^2, $^*P < 0.001$.

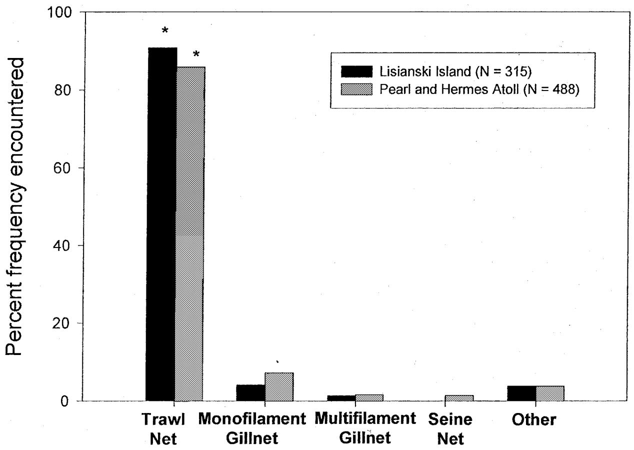

Fig. 7 Frequency of derelict fishing gear types encountered at Lisianski Island and Pearl and Hermes Atoll, NWHI.

second most frequent derelict net type at both sites was monofilament gillnet, representing 4% of nets by type at LIS and 7% at PHA. Multifilament gillnet, seine netting, and hard plastic items were also present, each composing less than 2% of debris by type at both sites. There was no significant difference in debris type frequency distribution between LIS and PHA (Heterogeneity χ^2, $df = 4$, $p = 0.50$).

By weight, trawl netting represented the most debris recovered (35%), followed by monofilament gillnet (34%) for both sites combined. By site, trawl netting accounted for 55% and 31% of total debris removed by weight at LIS and PHA, respectively (Fig. 8). Monofilament gillnet accounted for 1% of debris removed by weight at LIS. Two monofilament gillnet panels or tans, each weighing 1818 kg, accounted for 94% by weight of PHA monofilament gillnet. Miscellaneous maritime line was the third most common debris type by weight, accounting for 40% and 18% of LIS and PHA debris, respectively. Hard plastic fragments, multifilament gillnet, and seine netting each composed less than 10% of debris by weight at both sites.

Entangled/associated organisms

No Hawaiian monk seals or green sea turtles were observed entangled in derelict fishing gear during the study, although both were regularly observed associating with such debris. An adult female monk seal was observed resting on a class two-sized trawl net fragment for three days on North Islet, PHA. Adult and juvenile monk seals of both sexes were observed actively investigating reef-hung derelict fishing gear at both sites. Green sea turtles were also encountered resting on submerged derelict netting.

14 invertebrate and 10 vertebrate organisms were documented on or within debris recovered at PHA (Appendix A). Invertebrates represented included an echinoderm, a sipunculid, a platyhelminth, and numerous arthropods (crabs, shrimp, and lobster). Vertebrate organisms included 10 species of teleost fish.

Debris fouling

Seventy-two percent of all debris recovered had light or no fouling for both sites combined (Fig. 9). For the two types of debris at PHA with sufficient sample sizes to compare fouling by debris type, trawl netting and monofilament gillnet, there was no significant difference in fouling level ($\chi = 3.43$, $df = 3$, $p > 0.25$). At LIS, the

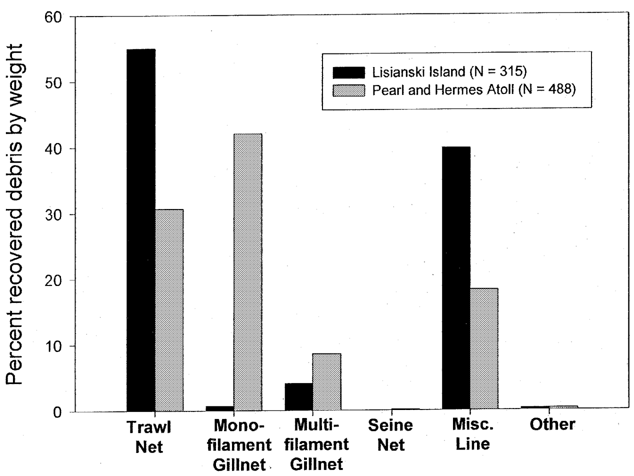

Fig. 8 Derelict fishing gear types recovered by weight at Lisianski Island and Pearl and Hermes Atoll, NWHI.

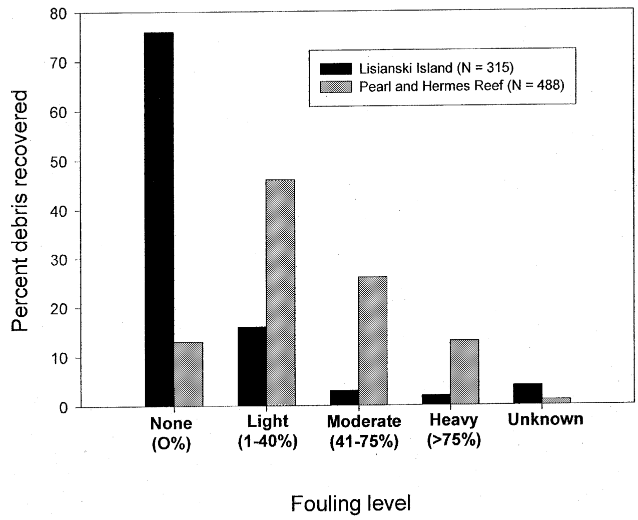

Fig. 9 Epibiont encrustation (fouling) level of derelict fishing gear recovered at Lisianski Island and Pearl and Hermes Atoll, NWHI, for all debris types combined.

rarity of debris types, other than trawl netting, prevented statistical comparison of fouling level among debris types because of low expected values (Zarr, 1984). Fouling level differed by location; PHA debris had significantly greater fouling than LIS debris $\chi^2 = 322.52$, $df = 3$, $p < 0.001$).

Discussion

Area surveyed, debris density and distribution

Although less than 1% of the coral reef habitat at LIS and approximately 8% of the coral reef habitat at PHA at depths of less than 10 m were surveyed, large amounts of derelict fishing gear were documented and removed during this study.

Assuming debris density is similar in surveyed and nonsurveyed LIS HERZ areas, 45 derelict fishing gear items may have remained in the LIS HERZ at the end of our study. Approximately 214 km^2 of coral reef habitat of less than 10 m depth occur at LIS outside the HERZ. If densities reported here for areas outside the HERZ are similar to those of the remainder of LIS reefs, 728 derelict fishing gear items may remain outside the HERZ at LIS.

Assuming debris density is similar in the surveyed and nonsurveyed PHA HERZ areas, nine derelict fishing gear items likely remained in the PHA HERZ at the end of our study. Approximately 203 km^2 of coral reef habitat at less than 10 m depth occur outside the HERZ at PHA. Debris removal from the Atoll's lagoon suggests large amounts of debris likely remain outside the HERZ at PHA, though lack of systematic surveys precludes an estimate.

Our benthic derelict fishing gear densities, 3.4–62.2 items/km^2, encompass the 53.0 items/km^2 found at French Frigate Shoals generated using similar methodology (Boland, unpublished data). Benthic debris densities in other regions have been generated using shipboard trawl surveys. Our results are similar to benthic debris densities of 4.5–25.0 items/km^2 for fishery-related items around Kodiak Island, AK (Hess *et al.*, 1999) and encompass the benthic debris density of 19.35 items/km^2 in the Western Mediterranean Sea (Galgani *et al.*, 1995). Our debris densities are greater than the 1.86 and 1.69 items/km^2 reported for the Eastern Bering Sea and Oregon Coast, respectively (June, 1990), but lower than that reported for the Bay of Biscay, 203 items/km^2 (Galgani *et al.*, 1995).

The extensive amount of derelict fishing gear recovered from the study sites' beaches indicates annual debris accumulation in the NWHI is high. Prior to 1999, when the US Fish and Wildlife Service modified regulations, entangling derelict fishing gear on NWHI beaches was annually incinerated in situ to prevent wildlife mortality. Consequently, beach debris recovered in the present study represents one year of terrestrial accumulation. Assuming debris is driven ashore at a constant rate, mean terrestrial derelict fishing gear accumulation rates at LIS and PHA are 4533 and 1140 kg/annum, respectively. Debris accumulation is undoubtedly modulated by the North Pacific Ocean subtropical high location relative to the NWHI, boreal winter storm intensity, and amount of fishing gear adrift. The latter a function of the frequency of gear use and loss in the North Pacific Ocean. Nonetheless, debris accumulation rates presented here, coupled with increasing Hawaiian monk seal entanglement trends since 1982 (Henderson, 2001), suggest derelict fishing gear is a chronic form of pollution affecting the NWHI.

Debris of maritime origins generated in the North Pacific Ocean is not distributed homogeneously on an ocean basin, archipelago, or atoll scale, disproportionately burdening NWHI coral reefs. Oceanographic models demonstrate debris originating throughout the North Pacific Ocean may ultimately accumulate in the region of the NWHI (Kubota, 1994; Wakata and Sugimori, 1990; Ingraham and Ebbesmeyer, in press). Wind-driven currents (Ekman drift), sea surface movement generated by wave energy (Stokes drift), and density-driven circulation (geostrophic currents) contribute to a convergence zone associated with the North Pacific Ocean subtropical high; regularly found around Hawaii and proposed as a mechanism for marine debris aggregation. Brainard *et al.* (2000a), using satellite sea surface wind measurements from 1992 to 1999, reported the NWHI intersect a region of high mean oceanic convergence, supporting Kubota's (1994) supposition that the mechanism for Hawaiian Archipelago debris accumulation is the convergence zone associated with the North Pacific Ocean subtropical high. The subtropical high and associated convergence zones are dynamic, varying on seasonal and annual scales. The subtropical high shifts southward during El Niño Southern Oscillation events, potentially subjecting the more southerly NWHI and main Hawaiian Islands to greater amounts of derelict fishing gear (Brainard *et al.*, 2000a). Using a coupled ocean-atmosphere model simulating drifters released uniformly over the North Pacific Ocean, Ingraham and Ebbesmeyer (in press) report drifter divergence in the subarctic region and high drifter concentration between approximately 25° and 35°N along longitudes 120°E to 130°W. Furthermore, freely drifting, or minimally drogued, buoys deployed throughout the North Pacific Ocean aggregate and remain in the region of the Hawaiian Islands (Kubota, 1994; Dotson *et al.*, 1977). Supporting these results, North Pacific Ocean marine debris surveys from 1986 to 1991 found the greatest densities of fishery-related marine debris from 25–35°N to 30–180°W (Matsumura and Nasu, 1997). Preliminary surveys of the US Line and Phoenix Islands found little evidence of derelict fishing gear (Brainard *et al.*, 2000b). Reports from other Pacific Island areas, and North Pacific Ocean oceanic convergence patterns, suggest the highest derelict fishing gear densities occur in the Hawaiian Archipelago (Brainard *et al.*, 2000a). Thus, much of the fishing gear set adrift in the North Pacific Ocean may eventually encounter and remain in the Hawaiian Islands, particularly the NWHI.

Within the NWHI, derelict fishing gear is common in shallow northern and interior atoll and island waters. The high debris density in the LIS HERZ is similar to that found in similar physiographic areas at French Frigate Shoals, NWHI (Boland, unpub. data). High debris densities in these areas support the mechanism by which derelict fishing gear is thought to enter atolls. Due to prevailing wind and current patterns, fishing gear adrift in the North Pacific Ocean would be expected to encounter more northeasterly outer barrier reefs. Once entangled on reefs, wind and wave forcing drags debris over the reef, ultimately coming to rest in shallow lagoons or on beaches. Our results suggest atoll physiographic characteristics influence whether derelict fishing gear is more likely to remain on reefs or be driven ashore, with implications for wildlife entanglement and mitigation efforts. At sites with extensive barrier reefs, and few emergent islets encircling a large lagoon, such as PHA, derelict fishing gear forced over the outer barrier reef may predominantly reside in relatively calm interior lagoon waters. Derelict fishing gear may be more readily deposited on beaches at sites with large emergent islands with relatively more shoreline, and indistinct or absent lagoons, such as LIS. Fivefold the amount of debris recovered from LIS' reefs was found on its beaches. In contrast, just one-seventh the amount of debris found on PHA reefs was recovered from its beaches.

Of the six Hawaiian monk seal subpopulations, the LIS subpopulation suffers the greatest entanglement (Henderson, 2001). For Hawaiian monk seals, beached derelict fishing gear may pose a serious entanglement risk, in addition to reef-hung debris. Entanglement is likely facilitated by the use of beached derelict nets by monk seals as a substrate upon which to rest on land, a behavior commonly observed throughout the NWHI. Actual entanglement rates likely exceed documented rates, as seals entangled at sea may drown unobserved. Entanglement rates at atolls such as PHA, where large amounts of derelict fishing gear remain in lagoons may be particularly subject to this bias. Thus, continued mitigation of derelict fishing gear entanglement by debris removal from both the terrestrial and aquatic critical habitat of the Hawaiian monk seal will enhance recovery of this endangered species.

Debris size

Although derelict fishing gear ranging in size from small net fragments to nearly complete trawl nets and gillnet tans was found at both sites, reef-hung debris size is consistent with our proposed accumulation mechanism. The nonuniform debris size distribution at LIS, with a preponderance of class 1 items, may result from the mechanical breakdown of derelict fishing gear as it is forcibly torn from reefs and driven ashore. In contrast, the uniform distribution of PHA debris size classes likely reflects both the mechanical breakdown of some derelict fishing gear, as well as maintenance of some large net fragments after deposition in calmer lagoon waters. The presence of seven derelict fishing gear items larger than 25 m^2, including two monofilament gillnet bundles, highlights the potential long-term impacts derelict fishing gear from distant fisheries poses to the coral reef ecosystems of the Hawaiian Archipelago.

Debris type

Gear type variety documented here supports the hypothesis that the NWHI are subject to marine debris generated from numerous greater North Pacific Ocean trawl, gillnet, and seine fisheries.

Although trawl netting is significantly more common than other types of derelict fishing net, no commercial trawl fisheries are conducted in the region of the Hawaiian Archipelago. Domestic and foreign trawl gear fishing occurs in Gulf of Alaska and Bering Sea waters providing potential sources for NWHI derelict fishing gear. Comparisons of beached derelict trawl net fragments recovered at PHA and St. Paul Island, Alaska, demonstrate moderate numbers of net fragments at both sites share construction characteristics and possibly sources (Boland *et al.*, 2000). Additional potential debris sources include trawl net fisheries conducted off the western coast of North America and in Japanese, Russian, Chinese, Korean, and Taiwanese waters. Additionally, this debris may originate from set-gear Asian fisheries using similar net construction and operating in shallow coastal waters (Al Burch, per. commun.).

Potential sources for monofilament gillnet recovered include drift gillnet fisheries targeting commercial pelagic species such as tunas and billfish conducted in Californian, Oregonian, and Mexican waters (WESPAC, 1995). High seas drift gillnets were widely used from the mid-1980s to early 1990s throughout the South Pacific and central North Pacific Ocean by Japanese, Korean, and Taiwanese fleets and may be a source of debris now found in the NWHI (WESPAC, 1995; Uchida, 1985). One large gillnet tan recovered in this study was first noted by researchers in the PHA lagoon in 1995 (Boland, pers. obs.). Additional potential derelict monofilament gillnet sources are the Japanese salmon driftnet fishery operating in the Russian far east economic zone (United States of America and Russia, 1999) and the US set-gillnet salmon fishery, which in 1998 alone consisted of 4000 vessels (Minton, 2000). Lastly, the large amounts of variously sized and configured recovered maritime line may be generated from fishing, other commercial, recreational, or military activities.

Debris fouling

The general lack of extensive organic growth, or fouling, on recovered derelict fishing gear may reflect short oceanic circulation histories, resistance to fouling organisms, or scouring. Floating derelict fishing gear may be a viable habitat for encrusting organisms, epibionts, and other biota as it circulates in ocean currents (see Winston *et al.*, 1997). Fouling extent may indicate relative time adrift, with more heavily coated debris of older origin. If so, derelict fishing gear documented here may have been discarded or lost relatively recently. A model of a uniformly dense deployment of freely drifting buoys throughout the North Pacific Ocean leads to a high-density area around Hawaii after just 400 days (Dotson *et al.*, 1977). Nonetheless, factors other than time adrift, such as sea surface temperature, epibiotic larval population abundance and recruitment, debris construction, and history of scouring influence fouling extent and confound debris age estimates based on fouling level. The extent to which debris is scoured of fouling organisms as a result of storms or other factors is unknown. Debris composed of synthetic materials may be manufactured or treated to resist organisms. Although definitive derelict fishing gear ageing by fouling level has not yet been investigated, Winston et al.'s (1997) suggested use of colony size and growth rates of key taxa to estimate minimum debris ages may be applicable in future studies of NWHI debris. Derelict fishing gear oceanic dispersal patterns may also be inferred from the presence on debris of key epibiont species endemic to different regions (see Gregory, 1987; Winston *et al.*, 1997 for examples).

Although most debris at both sites had little fouling, the greater fouling levels at PHA relative to LIS support the observed trends of debris fate at the two sites: predominant lagoon deposition at PHA and beach deposition at LIS. Derelict fishing gear entering the PHA lagoon may remain in the water longer than that at LIS, where debris will likely be driven ashore sooner. The oceanic convergence zone associated with the North Pacific subtropical high may intersect PHA more frequently than LIS, resulting in absolutely more debris accumulation at PHA, including debris of older, hence more fouled, origin.

Our study documented and removed fourfold the amount of debris recovered in an NWHI pilot study (Boland et al., unpublished data), but at significant logistical expense perhaps infeasible on a long-term basis. Availability of ship platforms and personnel needed to conduct such investigations may preclude the routine use of our methodology. Future marine debris clean-up costs may be redirected if technological advancements permit derelict net identification to owner through incorporation of unique chemical signatures in net materials or other types of net tagging; facilitating remuneration of removal costs from responsible parties.

The problem of derelict fishing gear is ideally addressed prior to its entrance into the marine environment, through enhanced compliance with MARPOL Annex V. Compliance will likely require an amalgam of moral suasion, incentive-based policies, education, and increased enforcement (Sutinen, 1997; Alaska Sea Grant, 1988). Currently, no cost estimate of the resource damage caused by derelict fishing gear in the NWHI exists. Nonetheless, Kirkley and Mc Connell (1997) and Smith *et al.* (1997)) suggest US of America citizens value aesthetic resources such as coral reefs and marine mammals and will support legislation to conserve them at a direct cost to themselves, even if the likelihood of ever personally experiencing the resource is low. As NWHI public access is limited, enhanced recreational value for this region – a common societal motivating value – will not drive societal actions toward mitigation of anthropogenic degradation of this region. Mitigation must be founded on societal values associated with vessel and wildlife entanglement reduction, ghost fishing reduction, and existence value (see Kirkley and Mc Connell, 1997, for a description of these values as they pertain to marine debris).

Future plans include revisiting previously cleaned sites to investigate debris accumulation rates, while continuing derelict fishing gear removal efforts. Additional work planned includes the examination of derelict fishing gear and its immediate environment for the presence of exotic invasive species.

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Appendix A

Organisms found on, or inside conglomerates of, recovered derelict fishing gear at PHA, NWHI:

Invertebrates
Arthropods:
Areolated xanthid crab (*Pilodius areolatus*)
Convex crab (*Carpilius convexus*)
Hawaiian cave shrimp (*Gnathophyllum precipuum*)
Hermit crab anemone (*Calliactis polypus*)
Jeweled anemone crab (*Dardanus gemmatus*)
Knotted liomera (*Liomera supernodosa*)
Marbled Shrimp (*Saron marmoratus*)
Red reef lobster (*Enoplometus occidentalis*)
Shrimp (*Palaemoninae* spp)
Violet-eyed swimming crab (*Carupa tenuipes*)
Echinoderms:
Spiny brittle star (*Ophiocoma erinaceous*)
Platyhelminths:
Lined fireworm (*Pherecardia striata*)
Sipunculids:
Peanut worm (Sipunculid spp)

Vertebrates
Teleost fish:
Eightstripe wrasse (*Pseudocheilinus octotaenia*)
Fantail filefish (*Pervagor spilosoma*)
Hawaiian whitespotted toby (*Canthigaster jactator*)
Leaf scorpionfish (*Taenianotus triacanthus*)
Potter's angelfish (*Centropyge potteri*)
Speckled scorpionfish (*Sebastapistes coniorta*)
Steindachner's moray (*Gymnothorax steindachneri*)
Two spot wrasse (*Oxycheilinus bimaculatus*)
Unidentified cardinalfish
Unidentified eel

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